AUTOMATIC CONTROL SYSTEMS

UDC 681.51 (045)

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NON STATIONARY MODEL OF ROBUST-OPTIMAL CONTROL SYSTEMS OF MARINE VEHICLES

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Abstract*—*Solution that improves marine vehicles control processes automation on the basis of variable structures robust-optimal systems in conditions of dynamic models of marine vehicles and environment uncertainty is considered in the report.

Index Terms—Decreasing error's values and energy costs; dynamic positioning of marine vehicles; optimal stabilization trajectories; robust circuits; robust-optimal systems; variable structure of feedback.

I. INTRODUCTION

The actuality of reducing the operating costs of the commercial and research fleet and the maritime safety improvement requires fundamental research in the development and application of reliable and comprehensive marine vehicles control systems that could facilitate safe manoeuvring in limited areas and implementation of the technical operations in the open sea.

At the same time, research of the methods of building autopilots for transport vessels shows the wide application of the PID-controllers, despite their well-known weaknesses in terms of the parameters setup, energy consumption and sensitivity to parametric noise. There for additional research is required to provide more effective and stable control systems. Requirements of the improvement of energy efficiency, time duration of the operational tasks and control accuracy, taking into account significant disturbances in the open seas, are relevant for the improvement of the existing dynamic positioning (DP) and maneuvering systems [1], [2].

The facilitation of movement on safe trajectories and marine vehicles accurate control under uncertainty conditions is based on development and practical application of robust-optimal control principles. This approach ensures the solution of the relevant functional tasks in a real time mode [3]. Implementation of the high technological performance requirements for maneuvering and positioning tasks of marine vehicles can be facilitated by the implementation of control processes based on the development of application systems with variable structure feedbacks. These systems are able to facilitate efficiency in terms of the energy costs reducing and the optimal control with sufficient invariance to the uncertainty of marine vehicles and environment.

II. PROBLEM REVIEW

The problem of vehicles stabilization in the researched operating mode or during driving on a predetermined path involves the creation of efficient and physically realizable applied control algorithms. For these algorithms, fundamental and ever-evolving element is the feedback control. There are some known approaches of feedback control: stabilization of motion of a dynamic system by static feedback based on the use of linear matrix inequalities, building a limited feedback with providing additional properties of transient processes, stabilization on the basis of quantitative feedback theory and many other approaches [4] – [7].

To ensure the process of marine vehicles control in DP mode we will consider the application of systems with variable structure feedbacks [8], [9] since the given approach under optimal control synthesis allows one to avoid some computation complexities for multidimensional dynamic models for marine vehicle and includes the main stages: designing the optimal trajectory; determining the switch time instants of controlling functions in the object feedback loop; the synthesis of controlling functions in the relevant feedback loops of multidimensional object.

Designing the optimal trajectory for the given boundary conditions consists in determining the required number of trajectory segments with constant values of the relevant arbitrary state coordinates and the switch time instants of controlling functions in the feedbacks loops when passing from the trajectory initial segment to the given one. Based on the analysis of diversity of the trajectories for the practical construction of marine vehicles stabilization trajectories with maximum performance or minimum energy consumption direct optimality conditions have been formed [8], [9]. In this case, one applies the generalized conclusion regarding the direct optimality conditions for practical construction of marine vehicle trajectories at positive values of derivatives of the state coordinate vector.

III. PROBLEM STATEMENT

Features of synthesis of control functions for the most general problem of marine vehicles stabilization in the dynamic positioning mode (Fig. 1) are considered in this paper. The problem of marine vehicles dynamic positioning in "safe circle" with a limited radius R (5–10% of the staying depth) is characterized by low speeds of permissible fluctuations of marine vehicles. It should be noted, that the high accuracy requirements to DP define constructive solutions for marine vehicles propulsion arrangement.

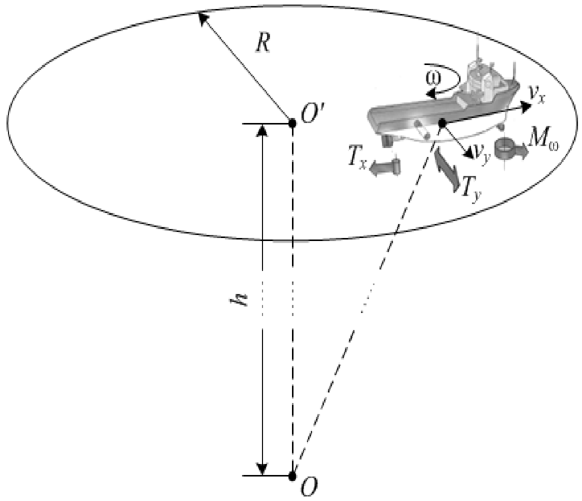

Fig. 1. Dynamic positioning of marine vehicle

In conditions by action of essential external disturbances, the control system of DP should be able to ensure the optimal speed stabilization of marine vehicles in "safe circle" at according criteria

$$J = \int_{t_1}^{t_2} dt = \min, \qquad (1)$$

where t_1, t_2 is the time of control process; and formation of control forces and moments with physically limited values for each controlled coordinate.

IV. SOLUTION OF THE PROBLEM

The dynamics of marine vehicles (excluding reaction of technological tool and external disturbances) in the horizontal plane can be represented as linear system of differential equations for the controlled axes: longitudinal horizontal v_x and transverse horizontal v_y speeds, angular speed ω of rotation (yaw) and heading angle ψ with respect to the center of mass taking into account accepted assumptions and values of the reduced inertia and flow coefficients [9]

$$\dot{\mathbf{V}}(t) = \mathbf{A}(\mathbf{V})\mathbf{V}(t) + \mathbf{B}\mathbf{U}(t), \qquad (2)$$

where $\mathbf{V}(t) = |v_x(t) \quad v_y(t) \quad \omega(t)|^{\mathrm{T}}$ are state coordinates vector; $\mathbf{U}(t) = |T_x(t) \quad T_y(t) \quad M_\omega(t)|^{\mathrm{T}}$ is the vector of control forces and moment; $\mathbf{A}(\mathbf{V}) = \begin{vmatrix} a_{11} & a_{12} & a_{13}v_y \\ a_{21}\omega & a_{22} & a_{23} \\ a_{31} & a_{32}v_x & a_{33} \end{vmatrix}$; $\mathbf{B} = \begin{vmatrix} b_{11} & 0 & 0 \\ 0 & b_{22} & 0 \\ 0 & b_{32} & b_{33} \end{vmatrix}$ are parameters and coefficients matrixes.

The dynamic models of stabilizing of the marine vehicle on the determined trajectories in the predefined safe area of the DP allows only small possible deviations of marine vehicles from the determined trajectory for providing accident-free functioning of the ship. At the small vibrations of the marine vehicle, quasilinearization of nonlinear dynamic models and elements of the stabilizing system allows to achieve analytical decisions, which describe the dynamic behavior of the system in real time and allows to derive qualitative motion characteristics of the dynamic system.

Closed-loop marine vehicle control system in the balancing mode with the following linear feedback

$$\mathbf{U}(t) = -\mathbf{K}\mathbf{V}(t),$$

with significant time of the controlled coordinates change, in comparison to the delay of control device [8], may be presented as

$$\dot{\mathbf{V}}(t) = [\mathbf{A}(\mathbf{V}) - \mathbf{B}\mathbf{K}]\mathbf{V}(t) = \overline{\mathbf{A}}(\mathbf{V})\mathbf{V}(t) \qquad (3)$$

where $\mathbf{K}$ is a matrix of static control regulator,

$$\overline{\mathbf{A}}(\mathbf{V}) = \mathbf{A}(\mathbf{V}) - \mathbf{B}\mathbf{K}.$$

Using decomposition in a Taylor series linearization, equation (3) can be presented in linear matrix form

$$\dot{\mathbf{V}}(t) \approx \overline{\mathbf{A}}(\mathbf{V}(0))\mathbf{V}(0) + \left[\frac{d\overline{\mathbf{A}}(\mathbf{V}(t))\mathbf{V}(t)}{d\mathbf{V}^{\mathrm{T}}(t)}\right]_{\mathbf{V}(0)} [\mathbf{V}(t) - \mathbf{V}(0)];$$

or

$$\dot{\mathbf{V}}(t) = \mathbf{R}\mathbf{V}(t) + \overline{\mathbf{R}}, \qquad (4)$$

where vector $\bar{\mathbf{R}} = [\bar{\mathbf{A}}(\mathbf{V}(0)) - \mathbf{R}]\mathbf{V}(0)$; matrix $\mathbf{R} = \left[\dfrac{d\bar{\mathbf{A}}(\mathbf{V}(t))\mathbf{V}(t)}{d\mathbf{V}^{\mathbf{T}}}\right]_{\mathbf{V(0)}}$.

Based on the proper matrix transformations we can find the solution of differential equation (4) as the following

$$\mathbf{V}^*(t) = e^{\mathbf{R}t}\mathbf{V}(0) + \int_0^t e^{\mathbf{R}(t-\tau)}\bar{\mathbf{R}}d\tau$$
$$= e^{\mathbf{R}t}\mathbf{V}(0) + \left[\int_0^t e^{\mathbf{R}(t-\tau)}\mathbf{R}(\mathbf{R})^{-1}d\tau\right]\bar{\mathbf{R}}$$
$$= e^{\mathbf{R}t}\mathbf{V}(0) + \left[\int_0^t e^{\mathbf{R}(t-\tau)}d\mathbf{R}\tau\right]\mathbf{R}^{-1}\bar{\mathbf{R}}$$
$$= e^{\mathbf{R}t}[\mathbf{V}(0) + \mathbf{R}^*] - \mathbf{R}^*,$$

where vector $\mathbf{R}^* = \mathbf{R}^{-1}\bar{\mathbf{R}}$.

With the account of the external measurable disturbances, the equation (2) will be written

$$\dot{\mathbf{V}}(t) = \bar{\mathbf{A}}\left[\mathbf{V}^*(t)\right]\mathbf{V}(t) + \mathbf{B}\mathbf{U}(t) + \mathbf{C}\mathbf{F}(t) \qquad (5)$$

where $\mathbf{F}(t) = \left| f_x(t) \quad f_y(t) \quad m_\omega(t) \right|^{\mathrm{T}}$ is the vector of external forces and moments; $\mathbf{C} = \begin{vmatrix} c_{11} & 0 & 0 \\ 0 & c_{22} & 0 \\ 0 & 0 & c_{33} \end{vmatrix}$ are coefficients matrixes.

The trajectory for the given boundary conditions will be speed optimal (1) when moving with maximum possible number of maximum possible values of derivatives of state coordinates vector considering restrictions on controlling action [9].

To ensure the motion on the given segments of stabilization trajectory we will determine the relevant controlling functions using the differential transformation of equation (5) with respect to the zero third second derivative $\ddot{\mathbf{V}}(t) = 0$ of marine vehicle speed vector taking into account the requirements for physical realizability of controlling propulsion device force. It allows us to form the balance equations of the reduced forces (moments) of control, damping and disturbance and their derivatives as well

$$\dot{\mathbf{U}}(t) = -\mathbf{B}^{-1}[\bar{\mathbf{A}}\mathbf{B}\mathbf{U}(t) + (\dot{\bar{\mathbf{A}}} + \bar{\mathbf{A}}^2)\mathbf{V}(t) + \bar{\mathbf{A}}\mathbf{C}\mathbf{F} + \mathbf{C}\dot{\mathbf{F}}], \qquad (6)$$

for zero third derivative $\dddot{\mathbf{V}}(t) = 0$

$$\ddot{\mathbf{U}}(t) = -\mathbf{B}^{-1}\{[\bar{\mathbf{A}}^3(t) + \bar{\mathbf{A}}(t)\dot{\bar{\mathbf{A}}}(t) + 2\dot{\bar{\mathbf{A}}}(t)\bar{\mathbf{A}}(t) + \ddot{\bar{\mathbf{A}}}(t)]\mathbf{V}(t) + \bar{\mathbf{A}}(t)\mathbf{B}\dot{\mathbf{U}}(t)$$
$$+ [\bar{\mathbf{A}}^2(t) + 2\dot{\bar{\mathbf{A}}}(t)]\mathbf{B}\mathbf{U}(t) + \mathbf{C}\ddot{\mathbf{F}}(t) + \bar{\mathbf{A}}(t)\mathbf{C}\dot{\mathbf{F}}(t) + [\bar{\mathbf{A}}^2(t) + 2\dot{\bar{\mathbf{A}}}(t)]\mathbf{C}\mathbf{F}(t)\}. \qquad (7)$$

Thus, a control system (Fig. 2, KSU is key switch unit) with a special structure feedback for multidimensional nonstationary linear model of marine vehicle is formed, which provides the movement on certain segments of the optimal trajectory with appropriate boundary conditions.

When solving practical problems of DP is necessary to compensate the deviation of marine vehicles from the center of positioning during the minimum time interval.

The transition of dynamic object from the initial segment to a predefined segment of the trajectory an taking into account the requirements of physical realizability of control is described by the following equations

$$\mathbf{X}(t_i^S) = \mathbf{X}(t_{i-1}^S) + \ldots \pm \overset{(m)}{\mathbf{X}}(t_{i-1}^S)\frac{(t_i^S - t_{i-1}^S)^m}{m!},$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots, \qquad (8)$$
$$\overset{(m-1)}{\mathbf{X}}(t_i^S) = \overset{(m-1)}{\mathbf{X}}(t_{i-1}^S) \pm \overset{(m)}{\mathbf{X}}(t_{i-1}^S)(t_i^S - t_{i-1}^S),$$

where $\mathbf{X}(t_i^p)$ are coordinates vector of marine vehicle; t_i^S is the switching moments of control on ith segment of trajectory.

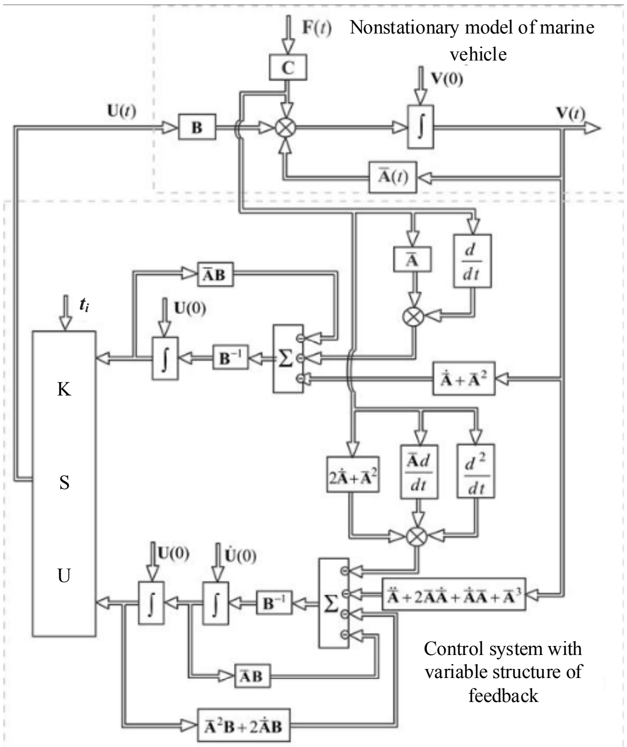

Fig. 2. Control system with variable stucture feedbacks

Further forming the equations of motion in the form (8) with the given boundary conditions for the coordinates of marine vehicle, and using the expression for the control functions of the form (6), (7), stabilization process of marine vehicle in a given area of operation is provided. For given boundary conditions and the values of the derivatives of the coordinates vector of the object defined within the constraints of the form (6), (7), based on the results of solving of algebraic equations systems (8), algorithms have been developed, including the introduction of leading, subleading and driven variables for multidimensional system, producing a sequence of moments of switching of control functions in feedback of control object.

A. Synthesis of Robust Control

To basic incomplete certainty at the control of marine vehicles, it is necessary to take:

1. Variation of parameters of mathematical model and physical object.
2. Uncontrolled (unmeasurable) external disturbances.
3. Parametric noises of measuring.

Solution of the problem of robust control of marine vehicles under conditions of incomplete certainty is based on use of the system with variable structure, which forms a reference model for the motion of the object taking into account controlled external disturbances. The control signal from the reference model goes to the input of physical marine vehicle (Fig. 3), and then in the circuit of robust control a correction signal is generated by comparing the output signal from the reference model with output of the control object.

The differential equation (5) taking into account robust circuit takes the form

$$\dot{\mathbf{V}}(t) = \bar{\mathbf{A}}(t)\mathbf{V}(t) + \mathbf{B}\left[\mathbf{U}_m(t) + \mathbf{U}_k(t)\right] + \mathbf{CF}(t). \quad (9)$$

For reference model equation (5) will take form

$$\dot{\mathbf{V}}_m(t) = \bar{\mathbf{A}}(t)\mathbf{V}_m(t) + \mathbf{BU}_m(t) + \mathbf{CF}(t). \quad (10)$$

For determining the a correction signal based on the linear equations (9), (10) obtain an approximate expression for the deviation vector $\mathbf{E}(t)$

$$\dot{\mathrm{E}}(t) \approx \bar{\mathbf{A}}(t)\mathrm{E}(t) - \mathbf{BU}_k(t). \quad (11)$$

Define the conditions for the generalized deviation of the dynamic positioning system

$$\ddot{\mathrm{E}}(t) + \mathbf{G}_1\dot{\mathrm{E}}(t) + \mathbf{G}_2\mathrm{E}(t) = 0, \quad (12)$$

where $\mathbf{G}_1$, $\mathbf{G}_2$ are matrices of weighting coefficients.

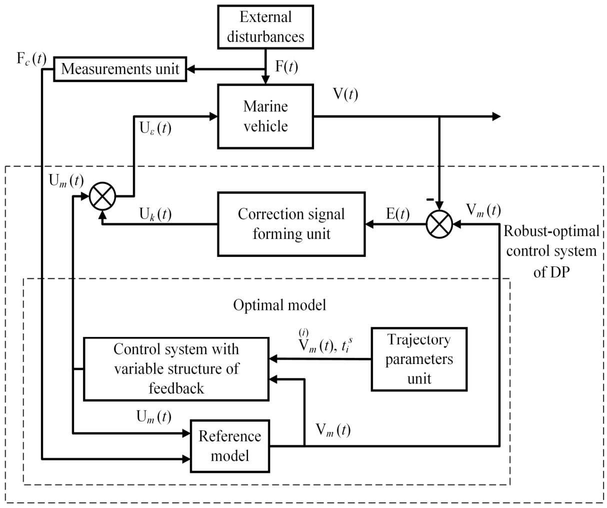

Fig. 3. Robust-optimal control system of DP of marine vehicles

Based on (11), (12) we obtain the dependence of correction robust control $\mathbf{U}_k(t)$

$$\dot{\mathbf{U}}_k(t) = \mathbf{B}^{-1}\left\{\left[\dot{\bar{\mathbf{A}}}(t) + \bar{\mathbf{A}}(t)^2 + \mathbf{G}_1\bar{\mathbf{A}}(t) + \mathbf{G}_2\right]\mathrm{E}(t) - \left[\bar{\mathbf{A}}(t) + \mathbf{G}_1\right]\mathbf{BU}_k(t)\right\}.$$

B. Modelling Results

The report presents the results of the DP simulation of marine vehicle to the beginning of the fixed coordinate system for linear and angular movement and speed (considered trajectories with zero second derivative of the vector of coordinates), which provides transients with a deviation less than 3% (Figs 4–9).

Uncontrolled external disturbances in the form of irregular sea waves were generated by the forming filter [8], parametric noise in the measurement of output coordinates generated by Gaussian white noise with corresponding intensity. The uncertainty of model of the physical object corresponding to the mathematical model of marine vehicle was set by varying parameters ± 15% of nominal values.

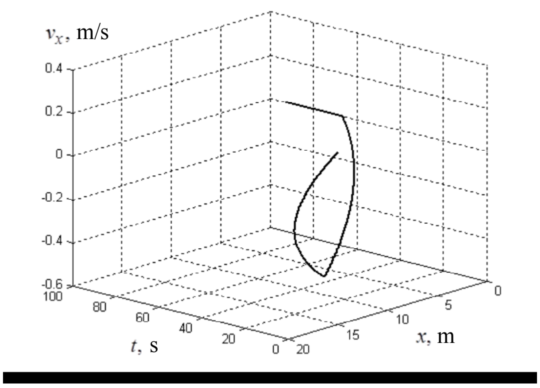

Fig. 4. Trajectories of controlled longitudinal horizontal coordinates

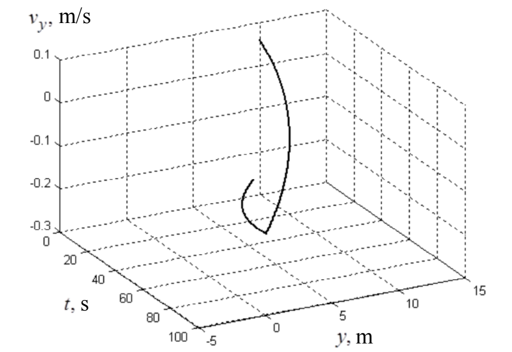

Fig. 5. Trajectories of controlled transverse horizontal coordinates

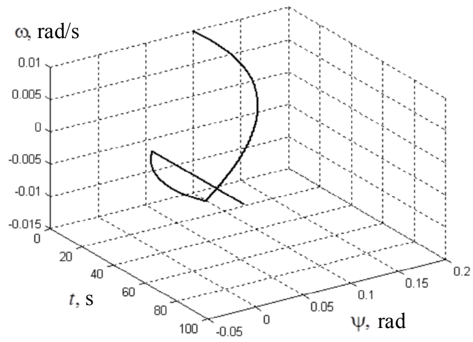

Fig. 6. Trajectories of controlled horizontal angular coordinates

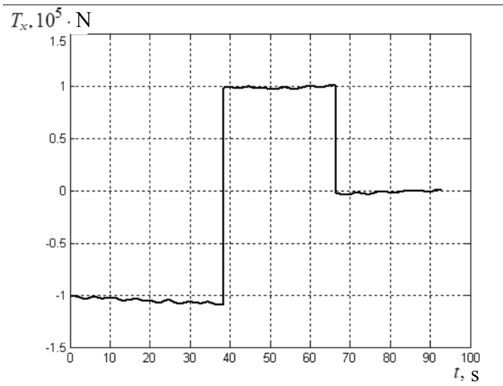

Fig. 7. Trajectories of control longitudinal force

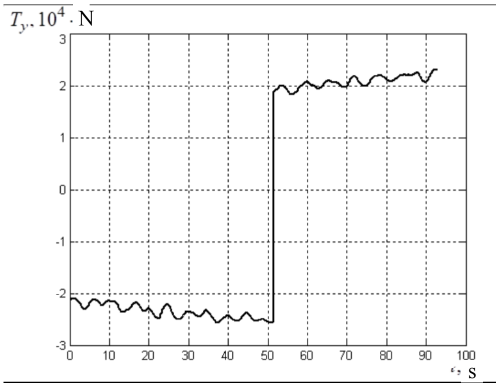

Fig. 8. Trajectories of control transverse force

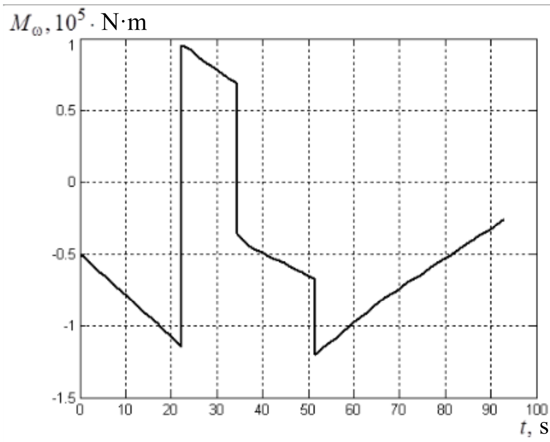

Fig. 9. Trajectories of control moment

V. CONCLUSIONS

The synthesis procedure of control functions based on systems with variable structure feedbacks is proposed. This procedure allows to resolve the optimization task of stabilization for direct optimality conditions of motion. Systems based on variable structure feedbacks allow to form the required control actions and to determine switching moments of controls in the feedbacks and facilitate the positioning of marine vehicle on optimal defined trajectories within the constraints on the control. In conditions of incomplete information about parameters of the marine vehicle model and uncontrollable external disturbances, robust corrective controls in combination with additional reference control signal provides the sufficient level of invariance to external uncontrollable disturbances and model uncertainty. The robust controls are based on the deviation of output controlled coordinates. Modelling examples demonstrate that proposed approach is more effective than number of existing control methods in terms of energy consumption and the value of the control deviations, and the availability of filtering properties of the control in feedback.

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Received April 19, 2016

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В. Л. Тимченко, О. О. Ухін, Д. О. Лебедєв. Нестаціонарна модель робастно-оптимальної системи керування морськими рухомими об'єктами

Представлено розв'язання задачі автоматизації процесів керування морськими рухомими об'єктами на основі робастно-оптимальних систем змінної структури в умовах нестаціонарності та невизначеності параметрів моделей морських рухомих об'єктів і навколишнього середовища.

Ключові слова: динамічне позиціонування морського рухомого об'єкта; робастно-оптимальна система; змінна структура зворотних зв'язків; робастний контур; зменшення помилок і енергетичних витрат; оптимальні траєкторії стабілізації.

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В. Л. Тимченко, О. А. Ухин, Д. О. Лебедев. Нестационарная модель робастно-оптимальной системы управления морскими подвижными объектами

Представлено решение задачи автоматизации процессов управления морскими подвижными объектами на основе робастно-оптимальных систем переменной структуры в условиях нестационарности и неопределенности параметров моделей морских подвижных объектов и окружающей среды.

Ключевые слова: динамическое позиционирование морского подвижного объекта; робастно-оптимальная система; переменная структура обратных связей; робастный контур; уменьшение ошибок и энергетических затрат; оптимальные траектории стабилизации.

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